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# Maximal $\nu_e$ oscillations, Borexino and smoking guns...

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## Abstract

We examine the maximal $\nu_e \to \nu_s$ and $\nu_e \to \nu_{\mu,\tau}$ oscillation solutions to the solar neutrino problem. These solutions lead to roughly a 50% solar flux reduction for the large parameter range $3 \times 10^{-10} \stackrel{<}{\sim} \delta m^2/eV^2 \stackrel{<}{\sim} 10^{-3}$. It is known that the earth regeneration effect may cause a potentially large night-day asymmetry even for maximal neutrino oscillations. We investigate the night-day asymmetry predictions for the forthcoming Borexino measurement of the $^7Be$ neutrinos for both maximal $\nu_e \to \nu_s$ and $\nu_e \to \nu_{\mu,\tau}$ oscillations. If $y \times 10^{-8} \stackrel{<}{\sim} \delta m^2/eV^2 \stackrel{<}{\sim} 4y \times 10^{-5}$ (with $y \simeq 0.5$ for $\nu_e \to \nu_s$ case and $y \simeq 1$ for the $\nu_e \to \nu_{\mu,\tau}$ case) then the maximal neutrino oscillations will lead to observable night-day asymmetries in Borexino and/or superKamiokande. With Kamland covering the high mass range, $10^{-5} \stackrel{<}{\sim} \delta m^2/eV^2 \stackrel{<}{\sim} 10^{-3}$ and Borexino/SuperK covering the low mass range, $3 \times 10^{-10} \stackrel{<}{\sim} \delta m^2/eV^2 \stackrel{<}{\sim} 5 \times 10^{-9}$ ("just so" region), essentially all of the $\delta m^2$ parameter space will soon be scrutinized.

Maximal oscillations occupy a special point in parameter space. Neutral Kaons and B-mesons both oscillate maximally with their antiparticle partners. Interestingly there is now strong evidence from solar [1] and atmospheric [2] neutrino experiments that electron and muon neutrinos also oscillate maximally with some as yet unidentified partner. Identifying these states is one of the most pressing issues in particle physics.

One possibility is that each of the three known neutrinos oscillates maximally with an approximately sterile partner. This behaviour is expected to occur if parity is an unbroken symmetry of nature [3,4]. In this theory, the sterile flavour maximally mixing with the $\nu_e$ is identified with the mirror electron neutrino. The characteristic maximal mixing feature occurs because of the underlying exact parity symmetry between the ordinary and mirror sectors. The maximal mixing observed for atmospheric muon neutrinos is nicely in accord with this framework (see e.g. [5]), which has the atmospheric neutrino problem resolved through '$\nu_\mu \to$ mirror partner' oscillations. Alternatively, it has also been suggested [6] that each of the known neutrinos are pseudo-Dirac fermions [7] which has each of the known neutrinos oscillating maximally into a sterile, $\nu_R$ partner. Both of these ideas motivate the study of maximal two flavour $\nu_e \to \nu_s$ oscillations (where $\nu_s$ means sterile neutrino).

Of course there are other possibilities. For example it is possible that the neutrino anomalies are due to bi-maximal mixing [8]. This sees the atmospheric anomaly being solved by maximal $\nu_\mu \to \nu_\tau$ oscillations and the solar problem being solved by maximal $\nu_e \to (\nu_\mu + \nu_\tau)/\sqrt{2}$ oscillations. The bi-maximal hypothesis is an interesting possibility even though a compelling theoretical motivation for it has yet to be found. Thus, two flavour maximal $\nu_e \to \nu_{\mu,\tau}$ oscillations (where $\nu_{\mu,\tau}$ means any linear combination of $\nu_\mu$ or $\nu_\tau$) is therefore also interesting. Note that the two phenomenologically similar (but theoretically very different) possibilities of $\nu_e \to \nu_s$ and $\nu_e \to \nu_{\mu,\tau}$ oscillations will hopefully be distinguished at the Sudbury Neutrino Observatory (SNO) [9] when they measure the neutral and charged current contributions separately.

Two flavour maximal oscillations between the electron neutrino and a sterile or active flavor produces an approximate 50% solar neutrino flux reduction for a large range of $\delta m^2$:

$$3 \ \times 10^{-10} \stackrel{<}{\sim} \frac{\delta m^2}{\mathrm{eV}^2} \stackrel{<}{\sim} 10^{-3}. \tag{1}$$

The reason why the reduction is not exactly 50% is because earth regeneration effects [10] can modify the night time rate (and there is also a small neutral current contribution in the case of active neutrino oscillations in $\nu e \to \nu e$ elastic scattering experiments). This earth regeneration effect can lead to a modest energy dependence, but not enough to explain the low Homestake result. The upper bound in Eq.(1) arises from the lack of $\overline{\nu}_e$ disappearence in the CHOOZ experiment [11][1], while the lower bound can be deduced from the observed recoil electron energy spectrum. For $E_{recoil} < 12\ MeV$ the recoil electron energy spectrum is consistent with an overall flux reduction of roughly 50% with no evidence of any energy dependent distortion of the neutrino flux. Maximal oscillations with $\delta m^2 \stackrel{<}{\sim} 3 \times 10^{-10}\ eV^2$

[1]Note that this entire range for $\delta m^2$ does not necessarily lead to any inconsistency with bounds imposed by big bang nucleosynthesis [12].

either significantly distort this spectrum or (in the case of very small $\delta m^2$) do not lead to any flux reduction (because the oscillation length becomes too long for oscillations to have any effect). Note that there is a hint of a spectral anomaly for $E_{recoil} > 12\ MeV$ [13] which may be due to "just so" oscillations [14] with $\delta m^2 \sim 4 \times 10^{-10}\ eV^2$ (see e.g. [15,16]) although it is also possible that it is due to a systematic uncertainty or statistical fluctuation.

The current experimental situation for solar neutrinos is summarized in the table below where the data is compared to the theoretical model of Ref. [17].

| Experiment | Flux | Theory |
|---|---|---|
| Homestake [1] | $2.55 \pm 0.25(stat + syst)$ SNU | $7.7^{+1.2}_{-1.0}$ SNU |
| Kamiokande [1] | $2.80 \pm 0.19(stat) \pm 0.33(syst) \times 10^6 cm^{-2}s^{-1}$ | $5.15^{+1.0}_{-0.7}\ 10^6 cm^{-2}s^{-1}$ |
| SuperKamiokande [1] | $2.44 \pm 0.05(stat) \pm 0.08(syst) \times 10^6 cm^{-2}s^{-1}$ | " " " |
| GALLEX [1] | $77 \pm 6(stat) \pm 5(syst)$ SNU | $129^{+8}_{-6}$ SNU |
| SAGE [1] | $67 \pm 7(stat) \pm 3.5(syst)$ SNU | " " " |

Table Caption: Comparison of solar neutrino experiments with the solar model of Ref. [17].

As the above table shows, the approximate 50% flux reduction implied by maximal neutrino oscillations in the parameter range, Eq.(1) would reconcile four out of the five experiments which means that this solution is in broad agreement with the experiments. The misbehaving experiment is Homestake which is roughly $3-4$ standard deviations too low (a 50% flux reduction would imply $\sim 3.3 - 4.5\ SNU$ c.f. the measured $2.55 \pm 0.25\ SNU$). If taken seriously, then the low Homestake results suggests some specific regions of parameter space [18]. However one should keep in mind that theoretical solar models involve a number of simplifying assumptions and it is therefore also possible that the $^7Be$ neutrino flux has been overestimated which would alleviate the discrepancy. Alternatively, there might be some as yet unidentified systematic error in the Homestake experiment. This seems plausible as the Homestake team argued that their data was anti-correlated with the sun spot cycle during the period before about 1986 (with high confidence level), but has since stabilized (see e.g. Ref. [19] and also section 10.5 of Ref. [20] for some discussion about this). We adopt the cautious viewpoint that this experiment needs to be checked by another experiment before a compelling case for large energy *dependent* suppression of the solar flux can be made.

Recently, Guth et al [21] pointed out that the earth regeneration effect [10] leads to a night-day asymmetry, $A_{n-d}$, for maximal neutrino oscillations. We define $A_{n-d}$ by[2]

$$A_{n-d} \equiv \frac{N - D}{N + D}. \tag{2}$$

Guth et al computed the night-day asymmetry for superKamiokande for large angle and maximal $\nu_e \to \nu_{\mu,\tau}$ oscillations. In Ref. [16] this was extended to maximal $\nu_e \to \nu_s$ oscillations where it was shown that the current measurements of the night-day asymmetry allow the parameter space $2 \times 10^{-7} \lesssim \delta m^2/eV^2 \lesssim 8 \times 10^{-6}$ to be excluded at about two standard

[2] Note that in the literature an alternative definition is also used which differs from our definition in Eq.(2) by an approximate factor of 2.

deviations. The point of this paper is to study both maximal $\nu_e \to \nu_s$ and $\nu_e \to \nu_{\mu,\tau}$ oscillation solutions in the context of the forthcoming Borexino experiment.

The Borexino experiment [23] is a real time $\nu e \to \nu e$ elastic scattering experiment like superKamiokande, but is designed to be sensitive to relatively low energy neutrinos. This should allow the neutrino flux from the $E = 0.86\ MeV\ ^7Be$ line to be measured. Our procedure for calculating the night-day asymmetry is very similar to Refs. [21,16] so we will not repeat the details here. One difference is that now we must use the zenith distribution function for the Gran Sasso latitude which we obtain from Ref. [22]. Also, we use the advertised [23,24] Borexino cuts in the apparent recoil electron kinetic energy of $0.25 < E_{recoil}/MeV < 0.70$. With this cut, about 80% of the recoil electron events are due to $^7Be$ neutrinos and 20% due to CNO and pep neutrinos [24].

Our results for the night-day asymmetry for the maximal $\nu_e \to \nu_s$ oscillation solution are given in figure 1 (solid line) and the maximal $\nu_e \to \nu_{\mu,\tau}$ oscillation solution is given in figure 2. Also shown (dashed line) is the analogous results obtained for the superKamiokande experiment obtained from Ref. [16]. Also included (dotted line) in the figures is the results for Kamland which may also be able to measure low energy solar neutrinos [25].

As far as I am aware, the night-day asymmetry for $\nu_e \to \nu_s$ oscillations (maximal or otherwise) has never been computed previously in the context of Borexino. While this paper was in preparation we became aware of the recent eprint, Ref. [26] which discusses the night-day asymmetry for large angle $\nu_e \to \nu_{\mu,\tau}$ oscillations in the context of Borexino. Our results are in agreement with the results of this paper when we examine the $sin^2 2\theta = 1$ line on their contour plot in the $\delta m^2, \sin^2 2\theta$ plane. For the subset of people interested mainly in maximal mixing our results are complementary to those of Ref. [26] since they contain more information than the contour plots.

The night-day asymmetry results for Borexino are roughly similar to the results for superKamiokande, except they are shifted to lower values of $\delta m^2$. This shift of about an order of magnitude in $\delta m^2$ is quite easy to understand. It arises because the typical neutrino energies for superKamiokande are about an order of magnitude larger than the energies relevant for Borexino and the oscillations depend on $E, \delta m^2$ only in the ratio $E/\delta m^2$.

Assuming maximal oscillations in the range, Eq.(1) (and the solar model of Ref. [17]), Borexino is expected [24] to detect around 25-30 events/day (with the cut $0.25 < E_{recoil}/MeV < 0.70$). This is somewhat more than in the SuperKamiokande experiment. Accordingly a night-day asymmetry as low as $A_{n-d} \sim 0.02$ (or even lower) maybe observable at Borexino after only a couple of years of data (see Ref. [27,26] for discussions of backgrounds and systematic uncertainties). From our figures we see that the maximal neutrino oscillation solutions lead to a significant (i.e. $A_{n-d} \gtrsim 0.02$) night-day asymmetry in Borexino and/or superKamiokande for the parameter range:

$$\begin{aligned} 5 \times 10^{-9} \lesssim \delta m^2/eV^2 \lesssim 2 \times 10^{-5}\ for\ \nu_e \to \nu_s \\ 10^{-8} \lesssim \delta m^2/eV^2 \lesssim 4 \times 10^{-5}\ for\ \nu_e \to \nu_{\mu,\tau} \end{aligned} \tag{3}$$

If $\delta m^2$ is in this range then the night-day asymmetry should provide a suitable "smoking gun" signature which could provide compelling evidence that the solar neutrino problem is solved by neutrino oscillations. This is especially important for $\nu_e \to \nu_s$ oscillations since it predicts that SNO will not find any anomalous NC/CC ratio.

Let us label the region in Eq.(3) as the "medium $\delta m^2$ region". Observe that there are two other possible regions of interest: The "high $\delta m^2$ region" with $2 \times 10^{-5} \stackrel{<}{\sim} \delta m^2/eV^2 \stackrel{<}{\sim} 10^{-3}$ and the "low $\delta m^2$ region" with $3 \times 10^{-10} \stackrel{<}{\sim} \delta m^2/eV^2 \stackrel{<}{\sim} 5 \times 10^{-9}$ (where the upper boundary is increased to about $10^{-8}$ for $\nu_e \to \nu_{\mu,\tau}$ oscillations). If $\delta m^2$ is in the high region then the Kamland experiment will be able to see reactor electron neutrino disappearance. This should fully test this region. Note that part of the high $\delta m^2$ region is already being probed by the atmospheric neutrino experiments. For large values of $\delta m^2 \stackrel{>}{\sim} 10^{-4} eV^2$, $\nu_e \to \nu_s$ oscillations lead to observable up-down asymmetries for the detected electrons [28]. At the moment there is no evidence for any electron up-down asymmetry which disfavours maximal $\nu_e \to \nu_s$ oscillations with $\delta m^2/eV^2 \stackrel{>}{\sim} 10^{-4}$ (similar results should also hold for $\nu_e \to \nu_{\mu,\tau}$ oscillations). For $\delta m^2$ in the low region the oscillations will lead to "just so" phenomena such as energy distortion and seasonal effects. These effects can be probed at superKamiokande for $\delta m^2/eV^2 \stackrel{<}{\sim} 10^{-9}$ (see e.g. [15,16]) and at Borexino for $\delta m^2/eV^2 \stackrel{<}{\sim} 5 \times 10^{-9}$ [29].

We summarize the current situation and expected sensitivities to $\delta m^2$ of the various experiments in figure 3 (for the maximal $\nu_e \to \nu_s$ oscillations) and figure 4 (for the maximal $\nu_e \to \nu_{\mu,\tau}$ oscillations). In the $\nu_e \to \nu_s$ case observe that all of the $\delta m^2$ parameter space will lead to a "smoking gun" signature in at least one of the experiments (Borexino, SuperKamiokande and/or Kamland). For the maximal $\nu_e \to \nu_{\mu,\tau}$ oscillations, there is a narrow region $5 \times 10^{-9} \stackrel{<}{\sim} \delta m^2 \stackrel{<}{\sim} 10^{-8}$ which may fall between the cracks. This region may possibly be tested at Borexino (or Kamland) if their systematic uncertainties can be reduced sufficiently so that $A_{n-d} \sim 0.01$ (cf.Ref. [26]) could be seen for the $^7Be$ neutrinos.

Finally, the current superKamiokande measurement of the night-day asymmetry is [30]

$$A_{n-d} = 0.033 \pm 0.017 \ (stat + syst). \tag{4}$$

If we take the above hint seriously, i.e. that the superKamiokande night-day asymmetry is small but non-zero then in the context of the maximal mixing scenario there are two possible regions for $\delta m^2$, depending on which side of the night-day "mountain" we are on. If we are on the left-hand slope then Borexino will see a large night-day asymmetry. Our results in figure 1,2 suggest a range of $0.12 < A_{n-d} < 0.20$ for the $\nu_e \to \nu_s$ case and $0.10 < A_{n-d} < 0.16$ for the $\nu_e \to \nu_{\mu,\tau}$ case. Of course if we are on the right-hand slope of the superKamiokande night-day mountain then Borexino will not see any night-day asymmetry. The shape of the superKamiokande energy spectrum of the night-time events can also tell us, in principle, which side of the night-day mountain we are on (see e.g. [21,16]).

In summary, there are strong general and specific theoretical reasons for neutrino oscillations to be maximal. This prejudice is broadly consistent with the $\nu_\mu$ disappearance observed by the atmospheric neutrino experiments as well as the $\nu_e$ disappearance suggested by the solar neutrino experiments. We have examined the predictions of maximal $\nu_e$ oscillations for Borexino (see figures 1,2). This experiment together with SNO, superKamiokande and Kamland should be able to cover essentially all of the parameter space of interest.

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**Figure Captions**

Figure 1: Night-day asymmetry, $A_{n-d} \equiv (N-D)/(N+D)$ versus $\delta m^2/\mathrm{eV}^2$ for maximal $\nu_e \to \nu_s$ oscillations. The solid line is the prediction for Borexino assuming a cut on the apparent recoil electron energy of $0.25 < E_{recoil}/MeV < 0.70$, while the dashed line is the night-day asymmetry for superKamiokande ($6.5 < E_{recoil}/MeV < 20$). Also shown (dotted line) is the corresponding result for the Kamland site ($0.25 < E_{recoil}/MeV < 0.70$).

Figure 2: Same as figure 1 except for maximal $\nu_e \to \nu_{\mu,\tau}$ oscillations.

Figure 3: Sensitivity of maximal $\nu_e \to \nu_s$ oscillations to the various experiments. Note that the "SuperK night-day" region denotes the region with an observable ($A_{n-d} \gtrsim 0.02$) night-day asymmetry at superKamiokande (which is not so large as to be excluded by the current superKamiokande data).

Figure 4: Same as figure 3 except for maximal $\nu_e \to \nu_{\mu,\tau}$ oscillations.

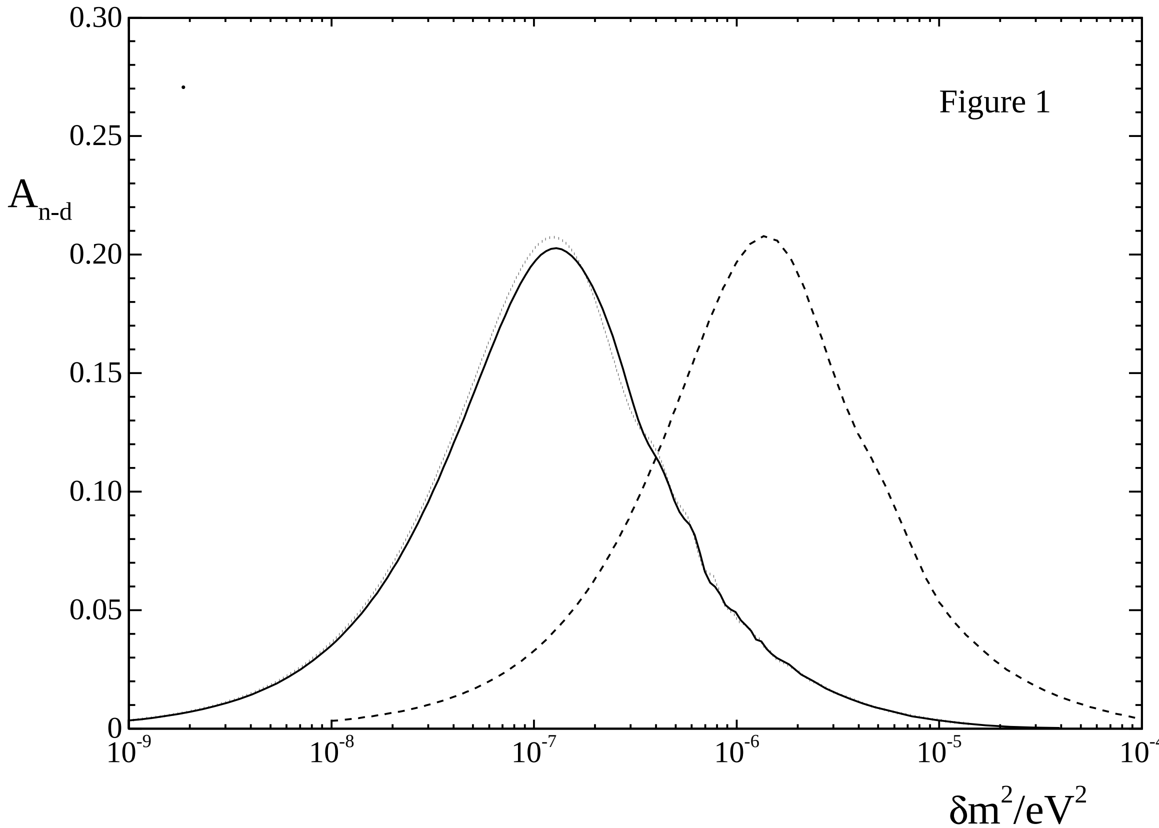
Figure 1
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$A_{n-d}$
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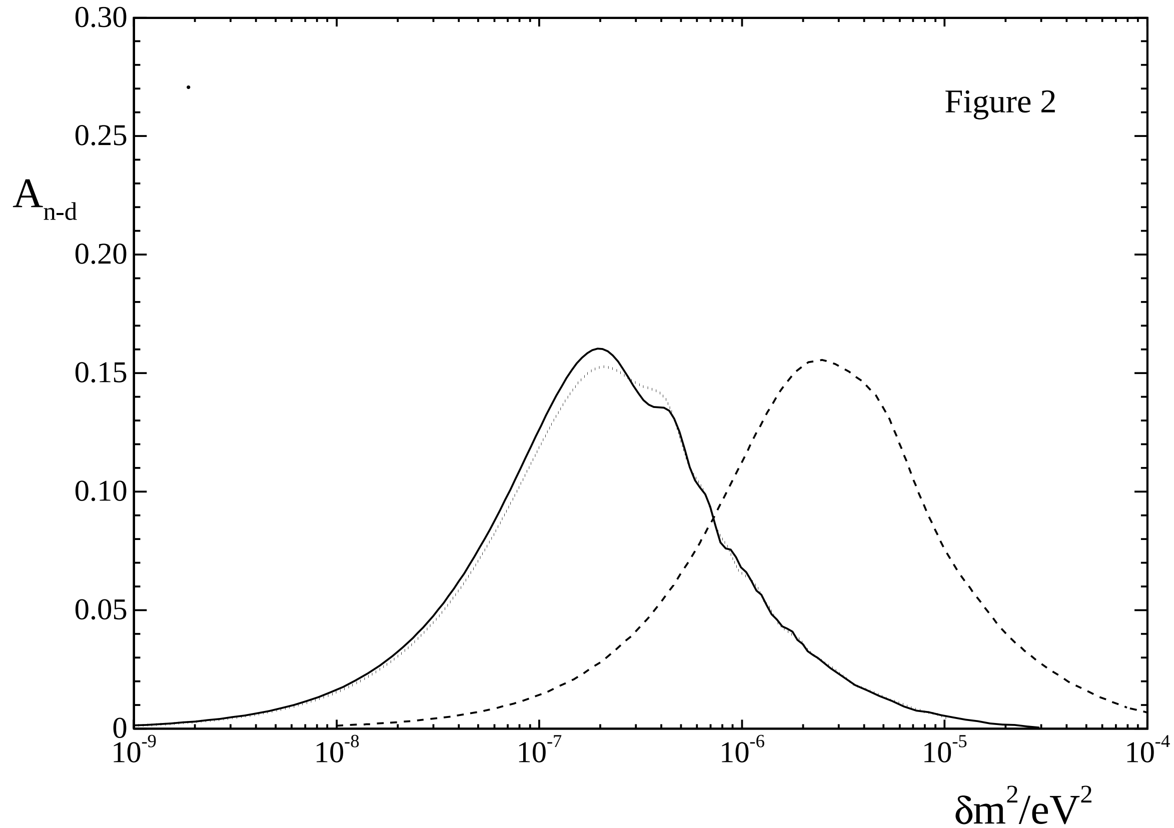

Figure 2
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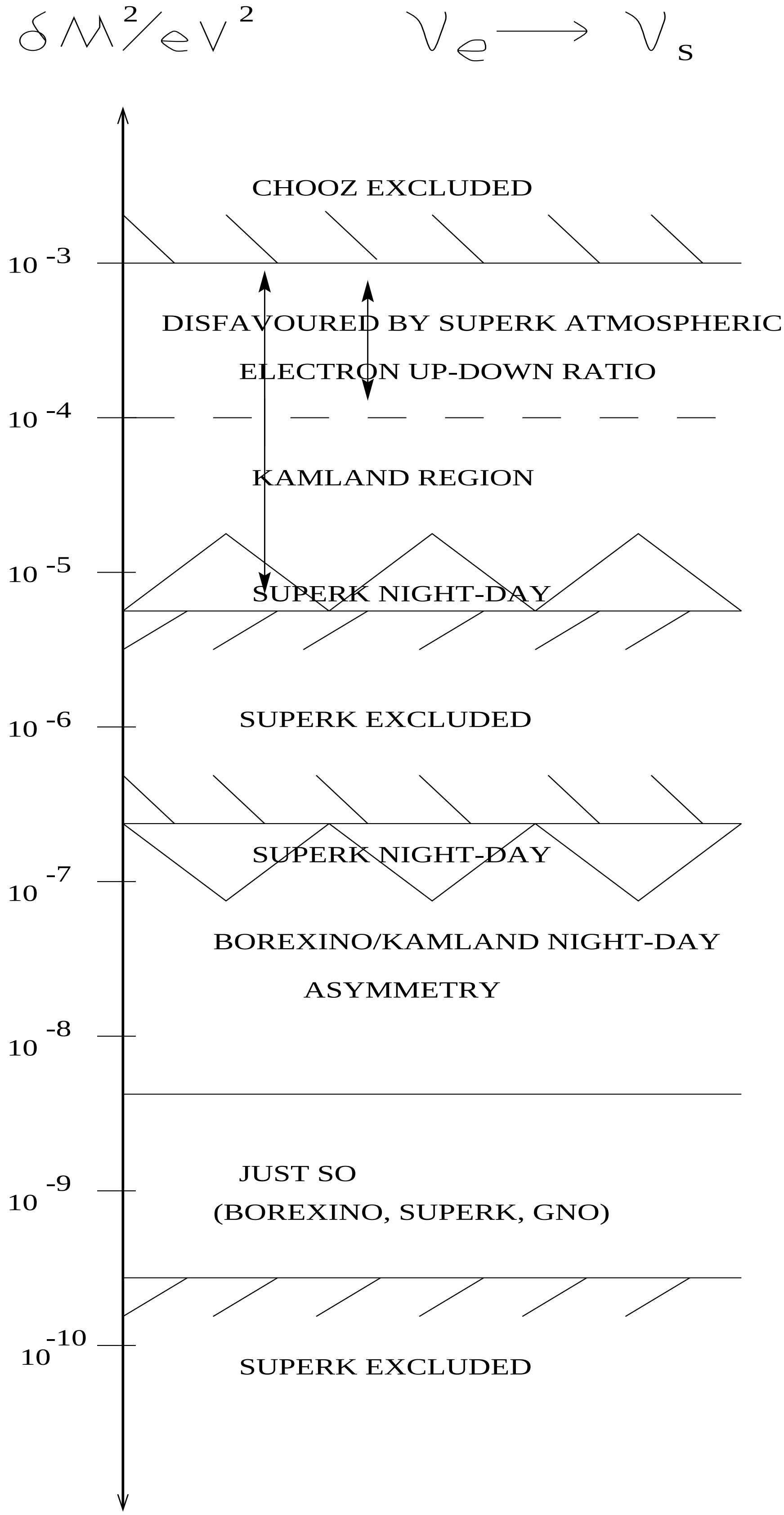
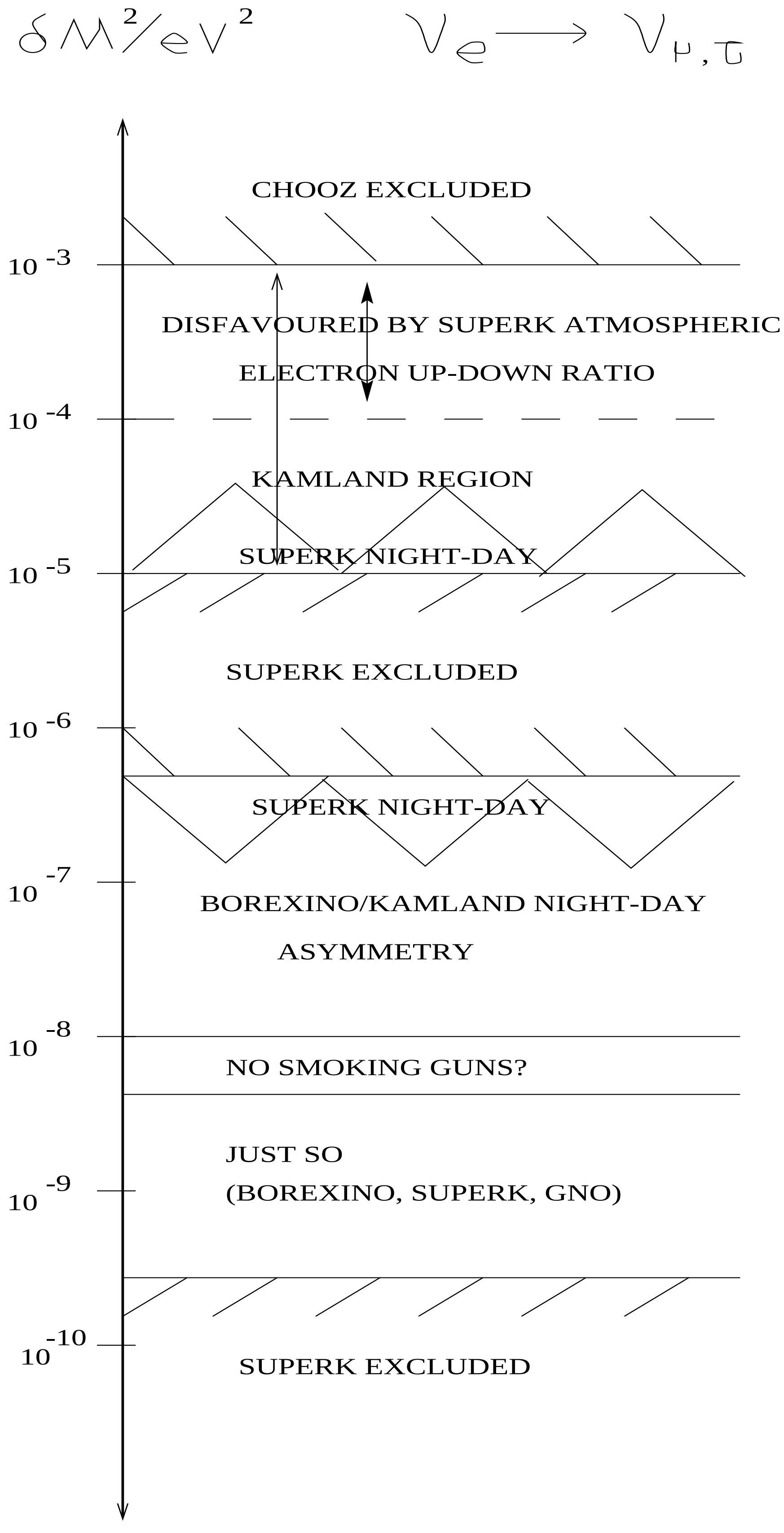


$\delta m^2/eV^2$
$\nu_e \longrightarrow \nu_s$
CHOOZ EXCLUDED
$10^{-3}$
DISFAVOURED BY SUPERK ATMOSPHERIC
ELECTRON UP-DOWN RATIO
$10^{-4}$
KAMLAND REGION
$10^{-5}$
SUPERK NIGHT-DAY
$10^{-6}$
SUPERK EXCLUDED
SUPERK NIGHT-DAY
$10^{-7}$
BOREXINO/KAMLAND NIGHT-DAY
ASYMMETRY
$10^{-8}$
JUST SO
(BOREXINO, SUPERK, GNO)
$10^{-9}$
$10^{-10}$
SUPERK EXCLUDED


δm²/eV²
ν_e → ν_{μ,τ}
CHOOZ EXCLUDED
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DISFAVOURED BY SUPERK ATMOSPHERIC
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KAMLAND REGION
SUPERK NIGHT-DAY
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SUPERK EXCLUDED
10 -6
SUPERK NIGHT-DAY
10 -7
BOREXINO/KAMLAND NIGHT-DAY
ASYMMETRY
10 -8
NO SMOKING GUNS?
JUST SO
(BOREXINO, SUPERK, GNO)
10 -9
10 -10
SUPERK EXCLUDED